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1.3 μm emission from 2 ML InAs quantum dots in a GaAs matrix

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Significant interest in self-assembled quantum dots (QDs) fabricated in situ during deposition of thin strained layer on a surface of a lattice-mismatched material is related to unique properties of these QDs and extraordinary device expectations [1]. One of the possibilities is to widen the emission range on GaAs substrates up to 1.6–1.8 μm. Recently, lasing at 1.3 μm was realized in such QD structures [2]. This laser was based on $In_{0.5}Ga_{0.5}As$ QDs which were grown by molecular enhanced epitaxy and effective thickness of InGaAs layer was 11 monolayers (MLs). Alternative way to shift the emission band is to lower the band gap of the matrix by inserting the InAs QDs in a narrow InGaAs quantum well (QW) [3]. Additionally to the narrowing of the matrix material band gap, the spinodal decomposition of the InGaAs alloy on stressors can be responsible for the long-wavelength shift of the emission. These effects potentially allow to utilize QDs formed on the initial stage of islands formation (effective thickness of the InAs layer is about 2 MLs $\approx$ 6 Å). Exactly these QDs are usually used for applications in injection lasers. This is related to the coherent nature of small QDs and low probability of formation of dislocated clusters. Small QDs are usually characterized by high surface density and fast carrier capture and relaxation processes. In this work we investigated the structural and optical properties of InAs QDs inserted in (In,Al,Ga)As QWs as a function of effective thickness of the InAs layer and the composition and thickness of QW. All samples were grown by molecular beam epitaxy on GaAs(100) substrates. Active region contains InAs QDs which were overgrown by $In_xGa_yAl_{1-x-y}As$ QW. Effective thicknesses of the InAs layer (d_{InAs}), and the QW region (L_{QW}) and the InAs (x) and AlAs (y) contents of the QWs for the investigated structures are summarized in the Table, where the data of transmission electron microscopy (TEM) are represented: QD density (ρ_{QD}), density of threading dislocations (ρ_{disl}) and linear density of in-plane misfit dislocations formed due to QDs (ρ_{lin}). The table also shows the results of optical studies: PL peak wavelength (PL_{max}), integral intensity of the ground state QD PL (I_{gs}), integral intensity of the PL (I_{int}) line, and the ratio of the intensities of the ground state QD PL and higher-energy lines due to smaller dots and excited states (I_{gs}/I_{ex}).

To realize a significant shift of the PL line from 1.1 μm for 2ML InAs QDs towards the 1.3 μm wavelength these 2ML QDs were overgrown by InGaAs QW with relatively large InAs content (samples #1 and #2). As it is seen from the Table 2 ML InAs QDs covered by 40 Å $In_{0.40}Ga_{0.60}As$ QW emit at 1.3 μm (samples #1 and #2). Sample #1 is characterized by high QD density (more than 10^{11} cm^{-2}), but the high InAs mole fraction in QW leads to the strong increase in dislocation density and degradation of optical properties (decrease of integral PL intensity). Using of submonolayer (sml) deposition mode (sample #2) for InGaAs QW allows to decrease ρ_{lin} and ρ_{disl} and to increase the PL efficiency (Fig. 1).

Table 1.

Sample	#1	#2	#3	#4	#5	#6	#7	#8
d_{InAs}, Å	6	6	6.5	7.5	8	9	9	6
x	0.4	0.4	0.18	0.18	0.18	0.18	0.12	0.15
y	–	–	–	–	–	–	–	0.15
L_{QW}, Å	40	40 sml	25	25	25	25	60	40
ρ_{QD} 10^{10} cm^{-2}	12	6.1	3.4	–	4.3	–	3.6	2.8
ρ_{lin} 10^{4} cm^{-1}	4.8	3.3	2.3	–	2.7	–	4	0.83
ρ_{disl} 10^{8} cm^{-2}	180	14	no	–	1.4	–	15	1.8
$\mathrm{PL_{max}}$, μm	1.30	1.31	1.24	1.26	1.27	1.27	1.30	1.32
I_{gs}	0.2	4	7	8	6	5	6.5	10
I^{t}_{int}	0.5	8	20	20	15	10	10	15
$I_{\mathrm{gs}}/I_{\mathrm{ex}}$	0.5	1.0	0.5	0.7	0.75	1.2	1.7	1.9

To investigate the influence of QD and QW parameters on structural and optical properties we changed the effective thickness of the deposited InAs layer keeping the constant parameters of InGaAs coverage (samples #3–6). One can see from the Table that, increase in the QD InAs layer thickness to 8 Å results in a shift of PL maximum to 1.27 μm and in an appearance of strong PL lines related to excited states in this case. Further increase in the InAs average thickness to 9 Å does not cause any significant shift of the emission band, but results in a decrease in the intensity of the excited state PL with respect to the ground state emission. In spite of the decrease in the integral intensity of the PL emission, the intensity of the ground state line remains constant. To shift the PL maximum further the InAs content in the QW was decreased and the QW thickness was increased (sample #7). This structure demonstrated 1.3 μm PL (Fig. 1) but was characterized by a high density of threading dislocations which is comparable with the case of sample #2 containing 2 ML QDs covered with an $\mathrm{In_{0.4}Ga_{0.6}As}$ layer.

Thus, both methods (utilizing small and larger QDs) allow to realize 1.3 μm emission and results in comparable structural and optical quality. However, the possibility to reduce the defect density to acceptable levels is not evident in these approaches. We found also that the dependence of the PL peak energy on In composition, or thickness of the InGaAs layer is not monotone. There exist a critical composition for the fixed thickness (or a critical thickness for the fixed composition, e.g. 4 nm for 20% InAs content), when the PL maximum shifts back to smaller wavelength with increase in either thickness or composition. We attribute this effect to appearance of high concentration of dislocated clusters which accumulate In from the InGaAs strained regions in their vicinity.

To reach the 1.3 μm range we also used additions of Al in the InGaAs alloy. Al additions are known to enhance the effect of decomposition of strained InGaAlAs QWs [4]. The effect is observed also for thick (In,Al)As layers [5]. Spontaneous formation of compositionally-modulated structures is reported by us earlier for InGaAs quantum wells, but the effect was less pronounced in that case [6]. In the present work the InAs QDs was used as strained precursors to stimulate the decomposition intentionally. This allows, using small (6 Å) QDs and 40 Å $\mathrm{In_{0.15}Ga_{0.7}Al_{0.15}As}$ QW (sample #8) to reach wavelength of

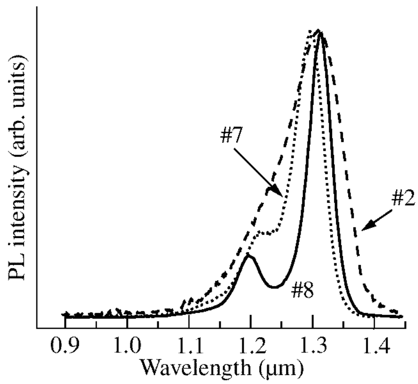

Fig. 1. PL spectra of investigated samples at $T = 300$ K.

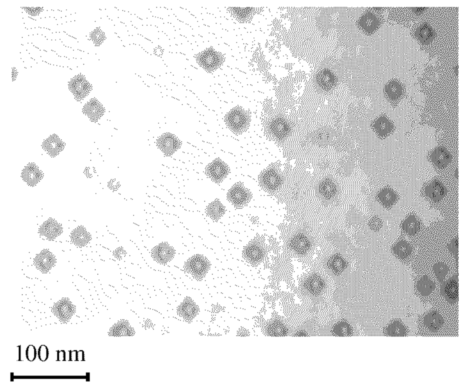

Fig. 2. TEM image of the sample #8.

1.3 μm (Fig. 1). This structure is characterized by relatively small density of 19 nm-large QDs (Fig. 2) but also, by low $\rho_{\rm lin}$ and $\rho_{\rm disl}$. Small concentration of dots indicates that some dots can be dissolved during the overgrowth process as it is also can be seen for other samples. This structure demonstrated a high intensity ratio between ground state 1.3 μm PL and high-energy PL peak. A relatively weak decrease of the PL intensity by one order of magnitude at moderate excitation densities is observed with temperature increase up to 300 K. Thus, addition of Al does not result in a strong degradation of quality of the alloy, deposited at the relatively low substrate temperature. Thus, we studied dependence of structural and optical properties of the structures with InAs QDs embedded in (In,Ga,Al)As QW and demonstrated the possibility to reach the 1.3 μm emission range by using 2 ML InAs QDs as stressors for stimulated alloy decomposition.

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